A STUDY ON RESTORABLE PRECAST PRESTRESSED HYBRID PIERS

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1.Introduction

Column members such as bridge piers that resist seismic forces are generally designed as ductile reinforced concrete members with enhanced energy absorption capacities. The fracture mode of members of this type is spalling of the cover concrete due to seismic forces, following which the vertical reinforcements buckle and strength is lost. If a member that has been damaged is to be reused, it needs to undergo a restoration process that typically includes strengthening or repair, such as retrofitting by wrapping in steel plates or adding concrete to increase the thickness. In addition, if there is a large amount of residual displacement, the need to restore the member to its original position in order to reuse it can be particularly problematic.

There have recently been suggestions of using a prestressed concrete column or pier to keep residual displacement to a minimum at the expense of energy absorption capacity.[1][2] This sort of approach is predicated on reuse of the member after an earthquake, and enables a design which will require as little strengthening or repair as possible. Nevertheless, since the prestressing steel still yields in such members, there may be a need to add additional steel or reinforcement the member in some other way to take account of low-cycle fatigue.

Given this background, there has not been sufficient debate concerning the incorporation of seismic performance in LCC (life cycle cost) calculations for bridges. For asset management purposes, engineers assess the risk of damage to a building using the concept of Probable Maximum Loss (PML), calculated as the maximum probable loss (repair cost)/cost of reconstruction x 100 (%). Since adoption of Japan's new anti-seismic design code in 1981, the PML for buildings has generally been considered to be in the range 10-20%.[3] Consequently, a similar approach has been taken to LCC assessment for bridges, in the belief that cost can be minimized. The corollary of this is that seismic design should not only be determined by initial cost, but should employ an approach to design that aims to minimize the cost of restoration after an earthquake while ensuring that the structure retains at least minimal functionality as a transportation route.

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This paper presents a structure for minimizing residual displacement after an earthquake while also keeping restoration costs to a minimum when the structure is reused.

2.Concept of a new structure

Figure 1 shows a proposal for a precast prestressed hybrid pier (P&PH pier) structure that can be reused, but which also reduces residual displacement after an earthquake. The proposed structure has the following characteristics.

- Composite structure comprising steel plates on the inside, and concrete on the outside
- Prestressing force is introduced only to the steep plates using external cables
- Segments are precast, and fitted together with un-welded metal-to-metal joints between the steel plates
- Concrete parts are jointed with non-shrink mortar, forming composite members with respect to compressive forces
- Joints between steel plates incorporate joint bars
- After an earthquake, pier performance can be restored by replacing damaged joint bars
- Shear forces are resisted by shear keys in the steel plates

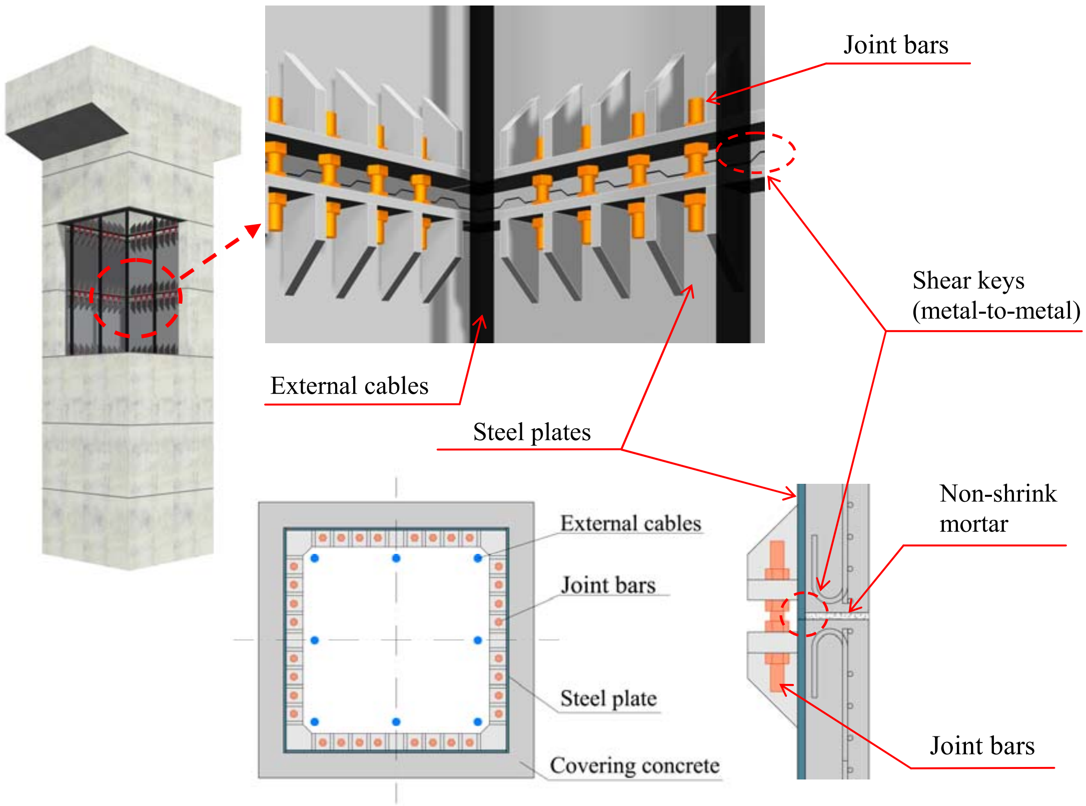


Fig. 1 Detail of P&PH pier

In general, since precast prestressed concrete piers have prestressing applied in the concrete section, a large amount of prestressing is required. In contrast, the P&PH pier only has prestressing applied to the steel plates, so the amount of prestressing required is only small. Also, since compressive forces are resisted as a composite structure with the concrete, the structure ensures that the steel plates are not subjected to excessive load. Furthermore, short steel joint bars are employed to act as yield members for the joints between segments, with the aim of absorbing a certain amount of energy through yielding of the joint bars without the steel plates yielding. As a result of this configuration, the proposed P&PH pier is a rational structure that maximizes the advantages of each of the individual materials and does not result in concrete spalling or yielding of the steel plates, and, because the steel joint bars employed as yield members only with short buckling length, the steel joint bars do not buckle. In addition, the structure also has the particular characteristic of being able to replace the members that are subject to damage, which enables the pier to be reused with only a small cost.

The aim of this research was to ascertain the seismic performance of the P&PH pier, so experiments were performed on a scale model to examine behavior under cyclic loading and to examine behavior after replacing damaged members.

3. Test Outline

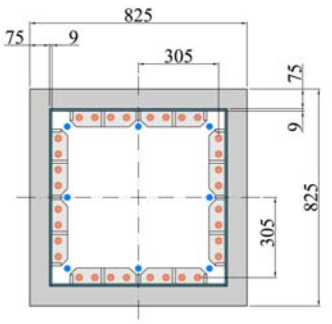
(1) Specimens

Envisaging an urban viaduct, the specimens were 1/4-scale models of a P&PH pier (full size: width 3.3 m x 3.3 m, pier height: 14.0 m, superstructure weight 8076 kN, external cables: 12S15.2 x 8). The model used as the specimen is shown in Figure 2. The pier itself consists of 6 segments (width: 0.825m x 0.825m, height: 0.500m, concrete thickness: 75 mm), with a total height of 3.250 m from the top of the footing to the loading point. Concrete strength is 60 N/mm^2 for the segments and 40 N/mm^2 for the footings. The steel plates have a thickness of 9 mm (SM490), and between the segments they incorporate shear keys (width: 20 mm-36 mm, height: 8 mm). The steel plates have metal-to-metal joints, and the bottom segment. 1, which forms the base of the pier, is joined by means of Perfobond shear connectors (PBL) embedded in the footing. Eight external cables are distributed around the perimeter of the central void, and the joint bars are M16 bolts (SS400), distributed around the whole of the perimeter. The cross-sectional area of the joint bars is calculated so as to be below the allowable stress for a level 1 earthquake, in contrast to the steel plates, which have thickness calculated so that the plates do not yield when subjected to a level 2 earthquake. In the specimen, the cross-sectional area of steel for one flange was 6075 mm^2 for the steel plate and 1256 mm^2 for the joint bars.

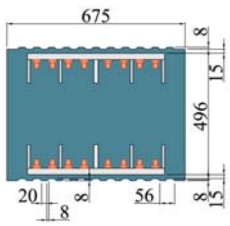
The initial axial compressive stress for the model of the pier was a total of 4.4 N/mm^2, including initial prestressing, the weight of the superstructure, and the weight of the pier.

(2) Loading steps

Since the structure is designed so that the joint section an ultimate state before the base of the pier, cyclic loading test is based on a displacement δy, at which the Joint 1 joint bars on the tension side yield. It was determined that the test would be performed by applying three cycles of cyclic loading that produce displacements that are an integral multiple of δy.
Figure 3 shows the loading steps used in the test, and Photo 1 shows the test rig at the time of the test.



Joint cross-section



Shape of steel plates

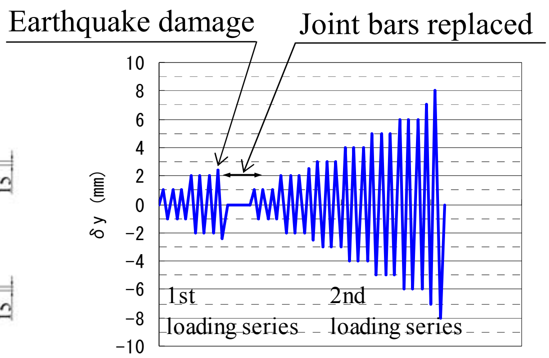
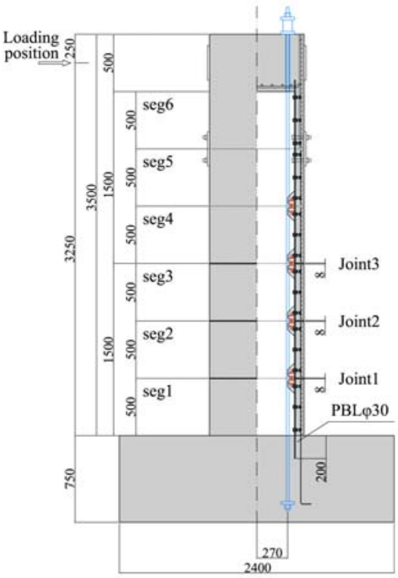


Fig. 3 Loading steps



Side view

Fig. 2 Specimen


Photo 1 Test equipment and model

In order to verify recoverability after earthquake damage, a first cyclic loading test series was performed first of all to produce earthquake damage in the specimen. Then, only the joint bars were replaced before performing a second cyclic loading test series. Reproduction of the earthquake damage focused on the joint bars in Joint 1, and the strain producing the damage was assumed to occur in the situation where maximum tensile strain was attained in dynamic analysis. The dynamic analysis, performed in advance, utilized E-W waves recorded on Kobe Port Island in the Hyogo-Nanbu Earthquake for ground type III.

4. Test Results

In the 1st loading series, the Joint 1 joint bars attained the standard strain for earthquake damage (the level set for this test) at a displacement of 2.4δy. At that point, the first loading series was terminated and the joint bars were replaced before performing the second series up to a displacement of 8δy. Figure 4 shows the load-displacement curves for both the first and the second series.

In the 2nd loading series, first of all a horizontal crack occurred in the base of the pier at 1δy and then at 2δy Joint 1 began to open. Maximum load was reached at 4δy, then when loading to 5δy one of the joint bars in Joint 1 began to fracture, resulting in a substantial decline in load. At that point, however, the segment showed no significant spalling of the covering concrete. At 7δy, all 16 joint bars in the plane subjected to loading in Joint 1 fractured, after which the decline in load became much smaller. Loading was continued but no significant opening was observed at any of the joints other than Joint 1. Furthermore, no significant damage was observed at the base of the pier, demonstrating that with this structure, damage is concentrated at Joint 1. The amounts by which Joint 1 and Joint 2 opened are shown in Figure 5.

Examining the load-displacement curve reveals a strong tendency to return to the original position when the load is removed, demonstrating that this structure can control residual displacement in a similar manner to other prestressed concrete structures. Furthermore, although the specimen was configured so that the joint bars are not subject to compression when the load is removed, it would also be possible to modify this configuration to produce a structure likely to absorb energy due to the hysteresis loop of the joint bars.

Regarding recoverability, the fact that no significant differences between the load-displacement curves for the 1st loading series and the 2nd loading series can be observed demonstrates that when the structure is subject to earthquake forces that damage the joint bars, the load resistance performance of the pier can be restored by replacing the damaged joint bars.

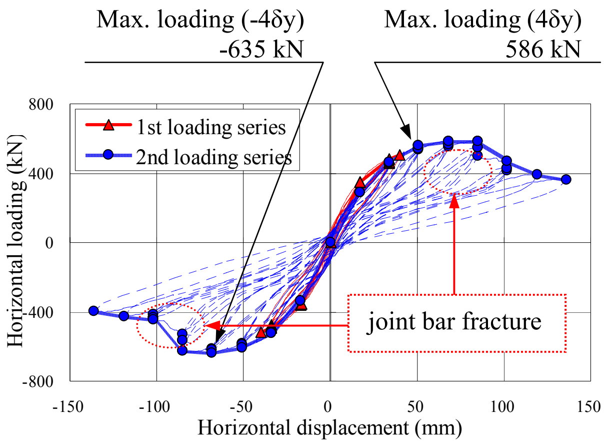


Fig. 4 Load-displacement curves

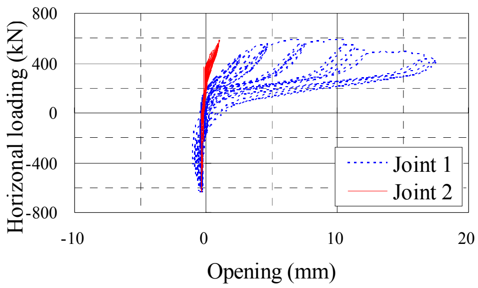


Fig. 5 Joint opening

5. Conclusions

In summary, the research drew the following conclusions about the proposed P&PH pier.

(1) The P&PH pier can control residual displacement after earthquakes in a similar manner to other prestressed concrete structures. Also, although cracking occurred in the base of the pier, damage was successfully restricted to the segment joints.

(2) Even after being damaged by an earthquake, it was possible to restore load-bearing performance by replacing joint bars.

Future research includes examination of ways to enhance performance, including increasing the energy absorption capacity by making the joint bars subject to compression.

References

1) Japan Prestressed Concrete Engineering Association: Seismic Design Guidelines for Prestressed Concrete Piers, November 1998

2) Minehiro Nishiyama: Unbonded Prestressed Concrete Joint Construction in New Zealand and the U.S.A., Journal of Prestressed Concrete, Japan Vol.45, No.4, pp.28-33, 2003

3) Japan Structural Consultants Association: Earthquake Risk and Probable Maximum Loss (PML), http://www.jsca.or.jp/vol2/15tec_terms/200409/20040929.html,2004.10